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14. ABSTRACT

The airborne microwave remote sensing was performed during EuroSTARRS using the Naval Research Laboratory STARRS instrument (Salinity, Temperature, and Roughness Remote Scanner). This leading edge passive L-Band instrument was acquired by NRL shortly before the campaign. Development of techniques for its use, and studies to understand its performance, are important parts of the acquisition process. In this paper we will examine instrument calibration and noise issues for STARRS which are associated with the flights conducted as part of the EuroSTARRS campaign, from November 16-23, 2001 in Germany, France and Spain. The issues we will address here are: pitch and roll improvements, L-Band absolute and ocean calibration, instrument stability, and environmental noise sources. A strong environmental noise source, located in the direction of Barcelona, was noticed during the Casablanca flight. A second environmental 'source' was noted in the analysis later. The high altitude section of the Casablanca flight has elevated TB (most notably in all the outboard beams) relative to the low altitude section of the flight. The effects such environmental (presumably man-made) sources Will have on satellite observations of L-Band brightness temperature may be significant.

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STARRS Calibration and Noise Issues for EuroSTARRS

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Introduction

The airborne microwave remote sensing was performed during EuroSTARRS using the Naval Research Laboratory STARRS instrument (Salinity, Temperature, and Roughness Remote Scanner). This leading edge passive L-band instrument was acquired by NRL shortly before the campaign. Development of techniques for its use, and studies to understand its performance, are important parts of the acquisition process. In this paper we will examine instrument calibration and noise issues for STARRS which are associated with the flights conducted as part of the EuroSTARRS campaign, from November 16-23, 2001 in Germany, France and Spain.

The issues we will address here are: pitch and roll improvements, L-band absolute and ocean calibration, instrument stability, and environmental noise sources. A strong environmental noise source, located in the direction of Barcelona, was noticed during the Casablanca flight. A second environmental 'source' was noted in the analysis later. The high altitude section of the Casablanca flight has elevated T_B (most notably in all the outboard beams) relative to the low altitude section of the flight. The effects such environmental (presumably man-made) sources will have on satellite observations of L-band brightness temperature may be significant.

Instrument Calibration

The instrument calibration corrections we present are pitch and roll improvements and the sky and ocean calibrations. The pitch and roll from the STARRS instrument were replaced, for this campaign, by the pitch and roll recorded by the DLR IGI high accuracy navigation system installed in the DLR Dornier-228. The improvement in pitch and roll between the STARRS data and the DLR data is shown in Figure 1. The key aspects to note are that the response of the STARRS gyro is too slow for the rapid manuevering of the racetrack survey flights, and that it is also noisier than the DLR pitch and roll data. However, there is a 12-13 second phase lag between the DLR data and

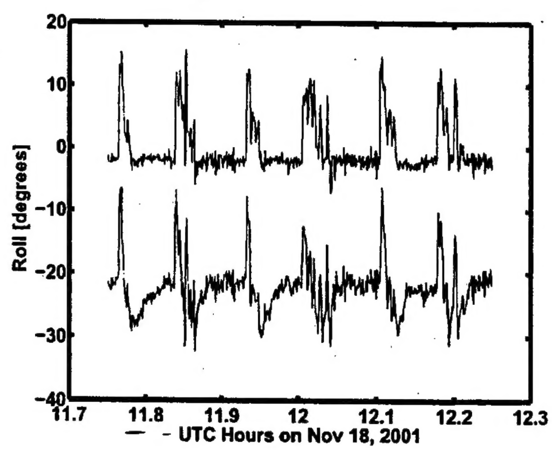

Figure 1: Roll from DLR IGI navigation system (upper curve) and from the STARRS gyro (lower curve) for an hour during the Nezer-Les Landes flight. The data are offset from each other for easier comparisons. The STARRS gyro response is noisier than the DLR response. STARRS gyro data also has long excursions in roll before returning to level flight that do not appear in the DLR data.

the STARRS data. This was first noted by Jacqueline Etcheto and her colleagues. A diagnostic for detecting the phase lag is plotting (for a single beam) the brightness temperature T_B versus roll angle. When the DLR recorded roll was out of phase with the actual roll by 12-13 seconds, these plots would show a rectangular pattern. The likely explanation for the phase lag is the difference between UTC and GPS time. The two systems typically differ by a few seconds.

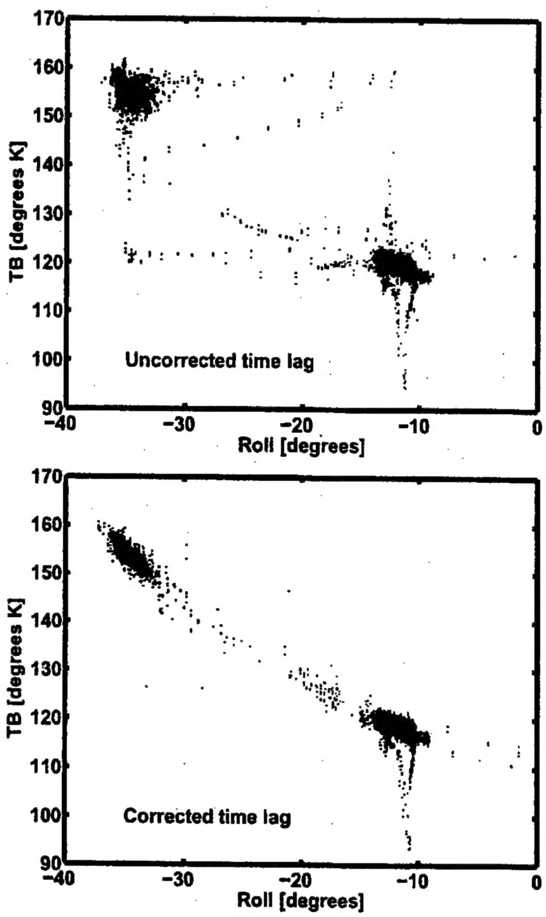

Figure 2: Brightness temperature versus roll for corrected and uncorrected time lags between the DLR pitch and roll and STARRS brightness temperature data for the ocean section of the Gascogne flight on Nov 17, 2001. The rectangular shape in the upper panel is due to the time lag between actual angle and recorded angle.

The instrument calibration is performed to determine coefficients of a linear relation between internal sensor temperature and voltages, and observed brightness temperature. It is difficult to find suitable targets for calibration of the instrument, for a variety of reasons. The instrument must be relatively far from a target (10m) in order for the beamforming to work (the target must be in the far field). In order for beam pattern effects to be eliminated, the target should emit uniformly and completely fill the field of view of the antenna. In addition, except for certain absorber materials, the relationship of brightness temperature to physical temperature is not known for some calibration targets - additional uncertainty arises in the calibration is due to this unknown factor. Finally, a relatively large range of temperatures must be spanned by the calibration targets. Calibration targets are presently available for two different temperatures: Calibration using the sky, at a very low absolute temperature dependent on the cosmic and galactic background radiation fields, and microwave absorber panels that are wrapped around the instrument and are kept at constant room temperature (280-300°K). Wrapping the panels around the instrument avoids the beamforming issues by presenting a uniform target to the antenna. The microwave absorber panels do have the characteristic that their physical temperature is the same as their brightness temperature (i.e. their emissivity $\equiv 1$) to a good approximation. Care is taken to find a sky calibration location that is large and open so that only the sky is observed by the instrument. The calibration is performed over 5 to 10 hours and at night. The calibration relation idetermined for STARRS is (Goodberlet, 2002)

$$T_A = a_0 + a_1 t_W + a_2\gamma + a_3\gamma t_H + a_4 t_{FE} \qquad (1)$$

Where T_A is the observed antenna brightness temperature, t_W, t_H, and t_{FE} are the warm load, hot load and antenna feed temperatures, respectively, and $\gamma \equiv \frac{V_W - V_A}{V_H - V_W}$ is effectively the normalized antenna voltage. The coefficients, a_0 - a_4 are determined by multilinear regression. The dominant terms are the zero offset a_0 and the coefficient of γ, a_2. Values for the coefficients used for final calibrated data are included in Table 1 at the end of the paper.

The calibration temperatures are far from the ocean brightness temperatures, thus, errors in the calibration coefficients may produce large errors in brightness temperature if there are non-linearities in the brightness temperature response of the instrument. For this reason, adjustments based on the ocean salinity calibration were also applied to the data. The constraints imposed by ocean salinity can be used to improve the calibration. When salinity is known from in-situ observations, the brightness temperatures can be adjusted (using a fixed offset for each beam) so that calculated ocean salinity from STARRS is closer to the in situ values. The drawback to this approach, for ab-

solute brightness temperature calculations, is that the corrections are based on a model for the ocean salinity and brightness temperature. We have used the Klein-Swift model (Klein and Swift, 1977) to make this calibration adjustment. The STARRS T_B values over the ocean were quite variable (as will be discussed in the following section) so only a fixed offset was calculated for the campaign. A single offset value (for each beam) was chosen to optimize the agreement of STARRS mean salinity for both the Gascogne and Casablanca flights. The beam adjustments are listed in Table 2.

Instrumental Noise Characterization

In performing the analysis of the STARRS ocean data, large excursions (2-3°K) in brightness temperatures were observed. An example of this noise is shown in Figure 3. Although the very small time period noise is quite large, the more harmful noise (to environmental observations) is the 5 to 7 minute period variability in the data. This low frequency variability is not correlated between beams. Possible explanations for this noisiness in the data have been explored. One possibility is that sources on the horizon, or the airplane itself, were contributing to the observed brightness temperature. Thus, analysis of the full 360 degree beam pattern was considered. However, no proposed sources could explain the independent variation of the six beam temperatures. In particular, no suggested external source has a suitable period. Thus, it was concluded that the instrument behavior should be examined in more detail by performing controlled observations with STARRS. In order to eliminate external sources of microwave radiation, the instrument was wrapped in microwave absorber (front, back and sides), and then wrapped in metal screening, in order to completely isolate the instrument from the environment. Steady state observation runs were then performed. In these runs two modes of operation were used, to determine any sensitivity of the instrument to its operating temperature. The instrument was either brought up to operating temperature and then heating was turned off - so that any switching effects of the heaters was eliminated, or the heating was kept on at very low levels. The absorber insulated the radiometer so that only modest heating was necessary to maintain operating temperature of approximately 35°C. Runs were from 4 to 16 hours long. Both methods produced virtually identical results in a statistical sense, eliminating the internal heaters (and their switching) as a possible source of the noise.

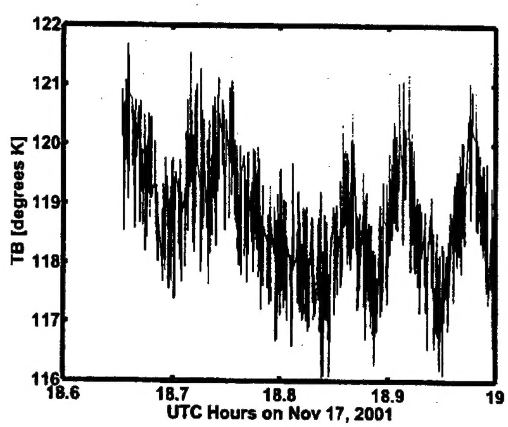

Figure 3: Brightness temperature for Beam 2R for a half hour in the Gascogne flight. Roll correlations have been eliminated. This data has a sampling rate of one sample per 0.45 seconds. The changes in brightness temperature correspond to changes in salinity of 4-5 psu, which is far larger than the in situ variability. The large excursions in the data have period of about 5 to 7 minutes.

To best evaluate the nature of the noise in the system, stable sections were chosen and detrended before statistical analysis was begun. This eliminates any effect of the small thermal drift in the overnight runs. The noise level observed in the controlled runs was approximately as expected for a single point measurement. The standard deviation of the detrended time series varied from 0.6°K to 0.9°K for the six beams. However, it was found that the noise was not white noise. White noise has the characteristic that a time series of white noise that is boxcar averaged, with boxcar length (N) samples, has its standard deviation reduced by a factor of $1/\sqrt{N}$. In Figure 4 the STARRS time series that is boxcar averaged by progressively longer filters maintains much of the long period variation that is eliminated in the white noise data set. Instead, the noise is better characterized as 1/f noise. This type of noise is actually ubiquitous in physical systems (West and Shlesinger, 1990). It characterizes systems that have much longer 'memory' than white noise systems. This is shown in the Allan variance plot of Figure 5. Increasing the averaging does not reduce the standard deviation by the expected $1/\sqrt{N}$ factor, but by a much smaller factor.

The effect of this characteristic of the STARRS instrument is that averaging does not sufficiently reduce the variance of the noise in the signal to obtain 0.2 psu salinity resolution for 1km pixel sizes. For example, at 160kt (80 ms^{-1}) airplane speed, 1km takes approximately 12 seconds. Thus, with one sample per 0.45s, 24 samples would be averaged for each 1km pixel. Averaging a white noise system would reduce the noise by a factor of 4.9. The actual reduction in the variance

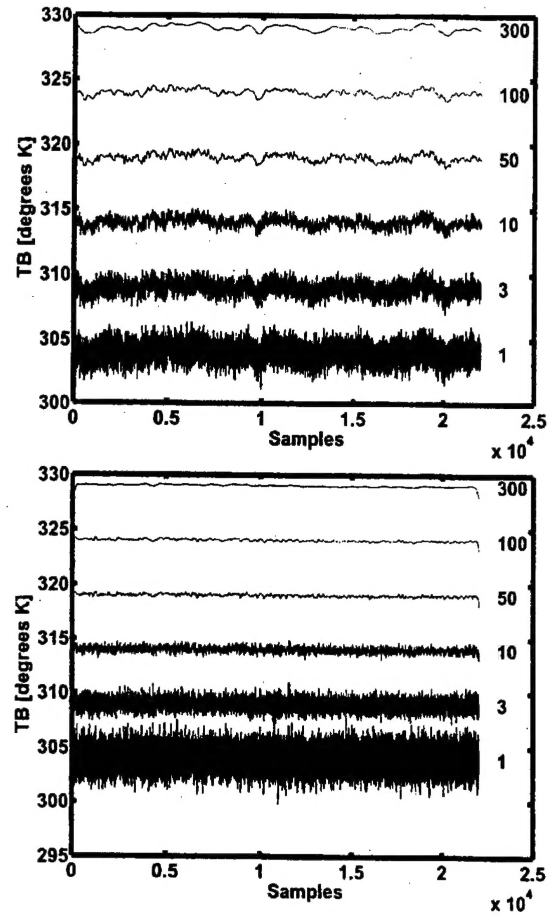

Figure 4: Brightness temperature for Beam 1R for a four hour in the period (upper box) and for the same length of a white noise signal (lower box). The progresively higher curves are the data after boxcar filtering with the number of samples shown on the right. The STARRS data has much more noise remaining after filtering with long windows.

of the STARRS data with a 24 sample boxcar average is, as indicated on the Allan variance plot (Figure 5), only a factor of about 1.6.

Work is underway to improve this aspect of STARRS L-band performance. This analysis has indicated possible changes to the internal calibration sampling software and hardware changes that should either reduce the 'system memory' of the L-band antenna, or reduce the single sample noise level sufficiently that observational accuracy goals can be met without resort to substantial averaging. The effect of this large noise on the EuroSTARRS data products may be substantial, depending on the accuracy

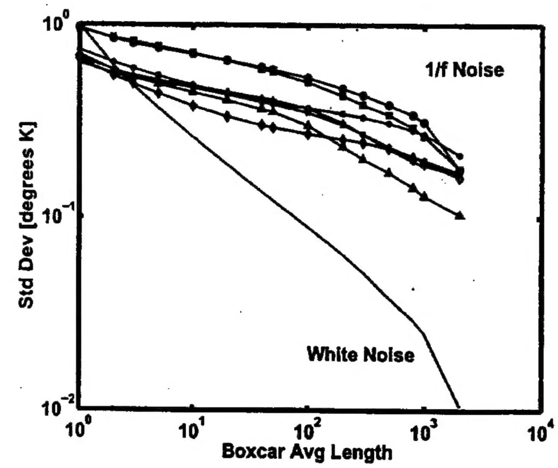

Figure 5: Variance in the time series for all six beams for a calibration run, as a function of the boxcar averageing length. The plain line is for white noise, while the upper line with circles is for $1/f$ noise.

requirements of the particular investigators.

Environmental Noise Sources

As part of the Casablanca ocean flight, circles were flown at a bank angle of 22°, in order to match the high incidence angle of the planned SMOS satellite. These circles were flown at 2700m altitude. A very high signal was observed centered on the time that the aircraft heading was 300°(see Figure 6). This heading corresponds to the beam swath pointing to Barcelona. All the beams were affected by this signal (even the beams on the opposite side of the plane), with the highest response in the outboard beam facing Barcelona. The question that this observation raises is: Besides the very high signal observed when STARRS was pointing directly at Barcelona, what more subtle effects do man made sources have on the STARRS brightness temperatures, and what effects would these sources have on a satellite based L-Band system such as SMOS?

A second observation from the Casablanca flight bears on this issue. The low and high altitude runs along the 40°N latitude line differ systematically in mean brightness temperature (see Figure 7). The outboard beams average over 4°K higher at high altitude than at low altitude, while the inboard (nadir pointing) beams differ by 1.5°K or less. Since all the observations were made within less than two hours, changes in the ocean salinity or temperature, which was obtained from the Casablanca in situ survey, can be ruled out as possible explanations for the differences between high and low altitude observations. The

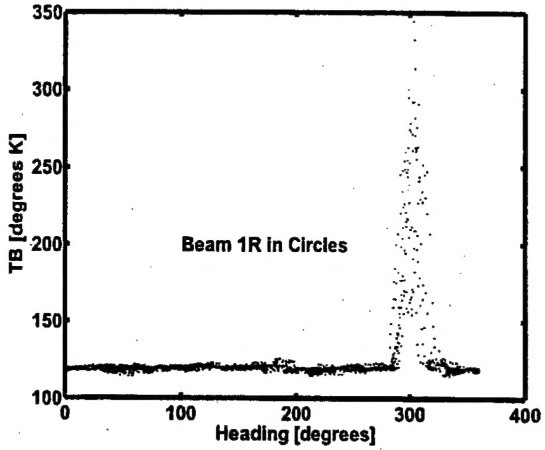

Figure 6: Brightness temperature for one beam (1R) during circular flight section of Casablanca survey (Nov 21, 2001). All beams were similarly affected by high T_B at a heading centered at 300°. There is also a small bulge in the signal at a heading of 180°, when the plane was nearest the coast and the STARRS swath was pointing to the west.

high and low altitude sections were flown in opposite directions, with the east-west segment at high altitude (Barcelona to the right of the plane). Since the high signals are coming from Barcelona, the source there may also affect the east-west run much more than the low altitude west-east run.

Other flights during the EuroSTARRS campaign were also examined for an altitude effect on brightness temperature. The Gascogne flight had a very short period of level flight at 170m, followed by a climb to 2700m. It had a similar pattern in the inboard and outboard beams, but the two sections of flight were not over the same water. The overall change was much smaller, but the relative pattern amoung the beams (inboard beam stays lowest relative to outboard beams at high altitude) was the same as for the Casablanca flight. The low altitude section was very near the coast and could have had substantially different salinity than the high altitude section further offshore. The Valencia flight on Nov 23, 2001 over a mixed agricultrual and forest site, had high and low altitude parts, but the 'low' altitude flight was at 1400m rather than the 170m flight level of the Casablanca flight. The high altitude section did have higher mean brightness temperatures, but they were small, and most likely due to warming of the ground during the daytime flight.

The changes observed during the Casablanca flight could be artifacts of changes in STARRS itself, due to the change in altitude and outside temperature, but this is unlikely. STARRS is internally heated to maintain its internal temperature. There is also a definite pattern of different brightness temperatures for all six beams between the low and high altitude sections. The sensitivity of the STARRS antenna, and in particular its rejection of strong signals in the side lobes of the antenna pattern, is not perfect. We cannot distinguish the source of the higher brightness temperature between a 'glow' at the horizon due to widely distributed man made sources, and a point source near Barcelona that is detected by STARRS at an oblique receiving angle. In either case, these observations indicate that external signals do influence the STARRS brightness temperature measurements. These signals appear to be stronger at high altitudes, because they are from sources near the horizon which are not 'seen' at low altitude.

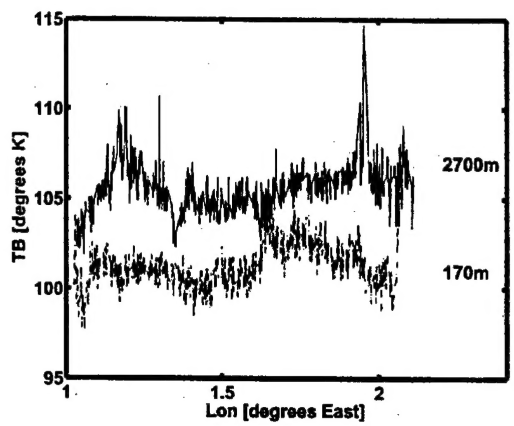

Figure 7: A demonstration of the bias in brightness temperatures induced apparently by altitude during the Casablanca flight (Nov 21, 2001) for beam 3L. The low altitude brightness temperatures are consistently lower than the high altitude brightness temperatures for all beams, but the largest bias is for the outboard beams.

Summary and Conclusions

The airborne remote sensing by STARRS provided L-Band brightness temperature data for land and ocean survey regions of the EuroSTARRS campaign. STARRS is a new instrument, and determining its performance and techniques for its best use are crucial to its development as a leading edge L-band microwave system.

We have summarized the calibration improvements and adjustments performed for the EuroSTARRS STARRS data. This includes improvement of the

pitch and roll data, and the ocean and sky calibration of STARRS. We have also demonstrated the characteristics of the noise in STARRS, particularly the $1/f$ character of the noise. Work is underway to improve the performance of STARRS based on this analysis.

We detected both large and small environmental sources of L-band energy during the Casablanca flight. When the beam swath pointed toward Barcelona during circling flights, a very large source was detected on all beams. The effect of this and other similar sources on airborne and satellite passive L-band systems may be substantial. A second environmental effect was that higher brightness temperatures were observed at high altitude than at low altitude for the repeated east-west line of the survey. We have tentatively concluded that this is due to detection of man made sources at the horizon, but cannot distinguish between a general 'glow' and a point source viewed obliquely. These observations of man made sources of L-band energy may, if confirmed, have substantial effects on other airborne L-band surveys and on satellite operations.

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Beam	a_0	a_1	a_2	a_3	a_4
3L	345.3	1.589	-304.0	-0.105	-0.5243
2L	350.9	2.455	-278.9	-0.304	-0.2073
1L	312.9	1.072	-364.1	-0.489	0.7919
1R	334.3	1.382	-429.4	-0.828	-0.0173
2R	346.1	2.718	-486.8	-1.888	-0.6977
3R	315.9	1.774	-451.1	-1.032	-0.0751

Table 1: Linear regression calibration coefficients for STARRS L-Band brightness temperature. These coefficients are a linear interpolation between calibration results from Sep 26, 2001 and Jan 26, 2002.

Beam	Offset °K
3L	-3.5
2L	-4.5
1L	-13.5
1R	-6.3
2R	-5.7
3R	-5.1

Table 2: Offset values for the STARRS L-Band brightness temperatures, determined from the in situ ocean salinity measurements of the Gascogne and Casablanca flights (Nov 17 and Nov 21, 2001).